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Environmental Security Technology Certification Program (ESTCP)

Flexible Reactive Berm (FRBerm) for Removal of Heavy Metals from Runoff Water

ESTCP ER-1213 Treatability Study

Steve L. Larson, W. Andy Martin, Mark S. Dortch,
Catherine C. Thomas, Chris S. Griggs,
and Catherine C. Nestler

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Environmental Laboratory

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Abstract

Small arms firing ranges (SAFRs) located on Department of Defense (DOD) facilities are, in many cases, constructed next to wetland areas. These wetlands represent a potential point of regulatory interest as they are at risk from heavy metal contamination. Access to wetland areas is typically limited due to a lack of roads. Standard environmental remedial options and monitoring techniques are expensive to implement due to the nature of the terrain and seasonal changes in water flow. Metals are highly associated with the soil particles making up the total suspended solids (TSS) in the runoff water. Reactive materials were assembled into a barrier similar to erosion control socks. Socks were constructed using a non-woven geotextile filled with well-graded sand, amended with five percent (weight: weight, w:w) iron/manganese-oxides (TRAPPS™) and/or five percent (w:w) treated apatite. The socks were tested under mesoscale lysimeter conditions and removal of metals from solution was confirmed. The reactive socks adsorbed greater than 95 percent of metals in the solution. Once the reactive material was exhausted, it was tested and found to pass the Toxicity Characteristic Leaching Procedure (TCLP) test for placement in a non-hazardous waste landfill. Positioning of the socks in the pathway of runoff water for the field demonstration was determined using predictive models for surface runoff.

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Preface

The work reported herein was conducted at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg. Funding was provided by the Environmental Security Technology Certification Program (ESTCP). The project is designated as ESTCP Project ER-1213: A Flexible Permeable Reactive Barrier for Protection of Wetland Sediments from Heavy Metals in Runoff Water.

This study was conducted under the direct supervision of W. Andy Martin, Branch Chief (EP-E); and Warren Lorentz, Division Chief (EP); and under the supervision of Dr. Patrick Deliman, Technical Director (EL) and Dr. Elizabeth Ferguson, Technical Director for Military Munitions in the Environment, ERDC-EL. Dr. Jack Davis was Deputy Director, ERDC-EL; Dr. Beth Fleming was Director, ERDC-EL.

COL Bryan S. Green was Commander of ERDC and Dr. Jeffery P. Holland was Director of ERDC.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
ounces (mass)	0.02834952	kilograms
ounces (U.S. fluid)	2.957353 E-05	cubic meters
pints (U.S. liquid)	0.473176	liters
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
quarts (U.S. liquid)	9.463529 E-04	cubic meters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter
yards	0.9144	meters

Acronyms

AFB	Air Force Base
AOI	Area of Interest
AOS	Apparent Opening Size
B	(fish) Bone, untreated
BB	Boiled (fish) Bone
BBB	Boiled and Bleached (fish) Bone, (3B)
BBBB	Boiled, Bleached and Baked (fish) Bone, (4B)
BMP	Best Management Practices
COTS	Commercial off-the-shelf
DDI S&S	Distilled, Deionized Water Suspend and Settle leaching test
DOD	Department of Defense
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FRBerm	Flexible Reactive Berm
ICP-AES	Inductively coupled plasma-atomic emission spectrometry
K_d	partition coefficient
NPDES	National Pollutant Discharge Elimination System
POA	Percent Open Area
pzc	Point of zero charge
SAFR	Small Arms Firing Range
SPLP	Synthetic Precipitate Leaching Procedure
TCLP	Toxicity Characteristic Leaching Procedure
USEPA	United States Environmental Protection Program

Metals

Antimony	Sb
Cadmium	Cd
Chromium	Cr
Copper	Cu
Iron	Fe
Lead	Pb
Magnesium	Mg
Manganese	Mn
Nickel	Ni
Uranium	U
Zero-Valent Iron	ZVI
Zinc	Zn

Compounds

NaCl	Sodium chloride

1 Introduction

1.1 Background

This project addresses the munitions residue-contaminated runoff water from training ranges that could potentially contaminate surface waters. Small arms firing ranges (SAFRs) located on Department of Defense (DOD) facilities are, in many cases, constructed next to wetland areas, including ponds, lakes, and streams. These wetlands, which may be seasonal, intermittent, freshwater, brackish, or estuarine, represent a potential point of regulatory interest, as they are at risk from heavy metal contamination in the runoff water from the adjacent active ranges. Access to wetland areas (especially forested wetlands) is typically limited due to a lack of roads. Standard environmental remedial options and monitoring techniques are expensive to implement, due to the nature of the terrain and seasonal changes in water flow and salinity. Thus, there is a need for a relatively low-cost, passive, in situ treatment technology for exclusion of toxic metals in runoff water that can meet the needs of the variable terrain.

This potential treatment is based on the proven use of a geotextile fabric woven into a tubular shape ("filter sock") and filled with sand. The filter sock is National Pollutant Discharge Elimination System (NPDES)-approved for use on construction sites in order to control transport of sediment in surface water. In a SAFR berm, metals occur in the form of discrete particles (e.g., intact munitions or fragments), as well as metal salts (e.g., weathering products), dissolved metal, or metallic complexes adsorbed to the soil matrix. When these soils are eroded, the particulate metals that are adsorbed to soils also move with the runoff water (Davis and McCuen 2005). Metal removal can be enhanced with the addition of innovative amendments to the sand that will adsorb both cationic (e.g., lead (Pb), zinc (Zn), and copper (Cu)), and anionic (e.g., antimony (Sb)) metals and/ or metalloids, and metals bound to suspended solids.

1.1.1 Amendments

The flexible permeable reactive barrier consists of sand and one or more amendments that will passively adsorb both dissolved lead and other metals, and prevent their transport in runoff water and into surface receiving waters or wetlands. The amendments provide for reduction of metal solubility through pH buffering of pore fluids within the barrier, as well as the sequestration of the metals through surface adsorption, and the precipitation of insoluble salts (Larson et al. 2005, 2007a, 2007b). Chemical amendments that were evaluated include phosphate compounds, and iron (Fe), and magnesium (Mg) oxide materials. Hydrous oxides of aluminum, Fe, and manganese (Mn) are ubiquitous in soils; and they are strongly implicated in the sorption of metals and reduction in metal mobility in soil systems (Bradl 2004, Covelo et al. 2007, Ford et al. 1997, Han et al. 2006, Komárek et al. 2013, Martinez and McBride 1998, Martinez et al. 1999, Ndiba et al. 2008, Orsetti et al. 2006, Trivedi and Ax 2000). The iron hydroxides are generally determined to be more effective at immobilizing Pb and less effective at immobilizing cadmium (Cd) and Cu. However, as the metal oxides age, the Pb was reported to undergo desorption. Unlike Pb, which had rapid initial sorption into ferrihydite, the metals with lower initial sorption (e.g., Mn) and nickel (Ni)) became incorporated into the more stable iron minerals, goethite and hematite, and remained immobilized (Ford et al. 1997, Martinez and McBride 1998). Cu, Pb, Ni, and Zn have also been reported to adsorb to Mn-oxide. Mn-oxide is a surface acidic oxide with a pH_{pzc} (point of zero charge) of approximately 1.5 to 4.5 (Han et al. 2006). Compared to controls, soil amendments containing phosphate reduced the leachability of these metal complexes by 89 percent (Ndiba et al. 2008).

The chemical amendments investigated in this study were two proprietary commercial mixtures of TRAPPS™, produced by Slater (UK) Limited. TRAPPS™, available as a commercial, off-the-shelf (COTS) product, is a formulation of apatite and other insoluble minerals, in which Pb is precipitated as stable pyromorphite. The other amendment evaluated was a biogenic phosphate derived from waste fishbone. The fishbones are identifiable by their open, mesoporous physical structure (Figure 1).

Raw fishbones can be treated to remove organic matter and increase the reactive surface area of the bone (Martin et al. 2008). The changes that occur in the physical and chemical characteristics of the biogenic apatite are shown in Figure 2 and Table 1. The treated fishbones are able to adsorb significant concentrations of heavy metals from solution (Larson et al. 2011) (Figure 3).

Figure 1. Crushed salmon bones (Apatite II™) under high magnification showing the mesoporous structure.

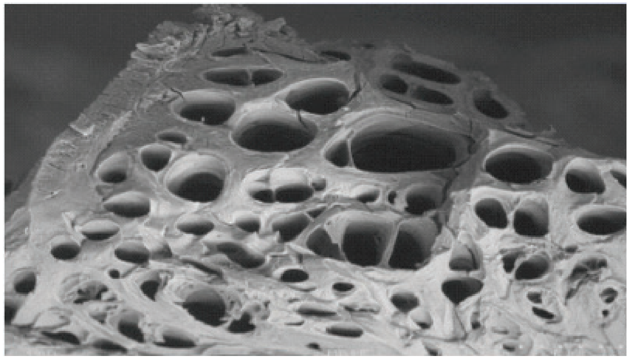
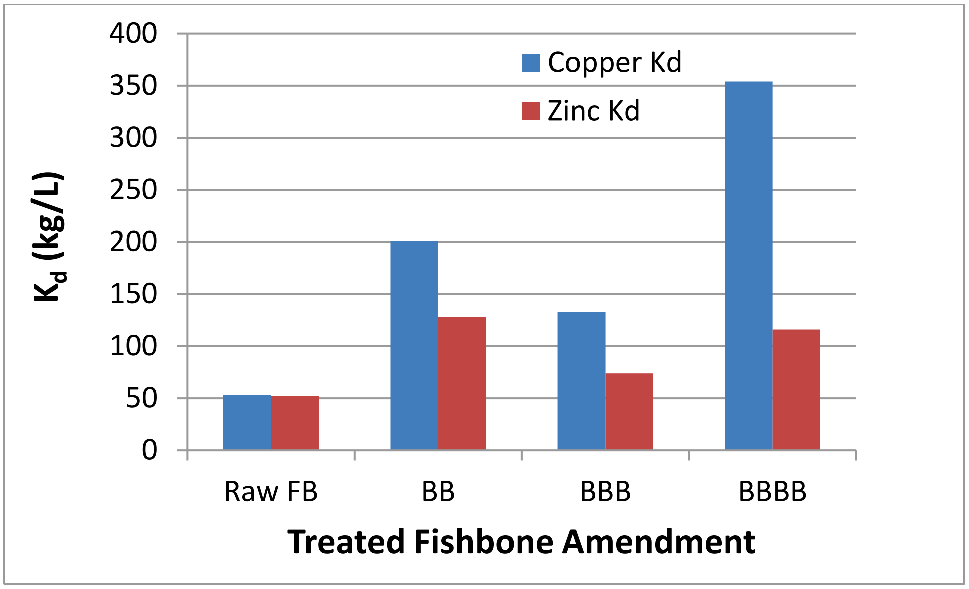


Figure 2. Physical changes in fishbone that occur during pre-treatment.

Table 1. Chemical changes in fishbone that occur during pre-treatment.

Parameter measured	Raw FB (B)	Boiled FB (BB)	Boiled and bleached FB (BBB)	Boiled, bleached, and baked FB (BBBB)
Biological oxygen demand (BOD) (mg/g)	>8.36	>8.36	>8.36	0.083
Surface area (m^2/g)	7.4	25.1	92.3	87.4
% with particle size <2.0 mm	0.0	29.4	45.4	80.0
% of initial mass	100	77.5	65.6	44.9

Figure 3. Comparison of K_d values for representative munitions metals (copper and zinc) in solution with treated fishbones.



1.1.2 Range sock

The U.S. Environmental Protection Agency (USEPA) has declared that sediment contamination of our surface waters is the greatest threat to our nation's water resources. Sediment carries particulate-bound metals and other contaminants. Research has shown that the majority of heavy metals leaving small arms ranges is associated with the suspended solids in the runoff water (Tardy et al. 2003). Common best management practices (BMPs) for controlling sediment transport include straw bales, mulch or compost blankets, and silt fences (Faucette et al. 2007). In 2006, the USEPA (USEPA 2006) added compost filter socks as an approved BMP for controlling sediment in runoff water. The use of filter socks resulted in significantly lower turbidity relative to bare soil (Bhattarai et al. 2011, Faucette et al. 2009b). These filter socks are now manufactured by several companies (e.g., Filtrexx International, Layfield Inc., and Propex) from different geotextiles and adhere to USEPA specifications for sediment transport (Faucette et al. 2009a). The different geotextiles have varying porosity, photodegradability, and life expectancy which must be matched to the site requirements and the different amendments. The weight of a filled sock (approximately 40 lbs / linear ft. for an 8" diameter sock, depending on the fill material) effectively prevents sediment migration beneath the sock. The sock is flexible and adheres to varying terrain and slopes (Figure 4).

Figure 4. Photograph of an erosion control filter sock in use under field conditions.

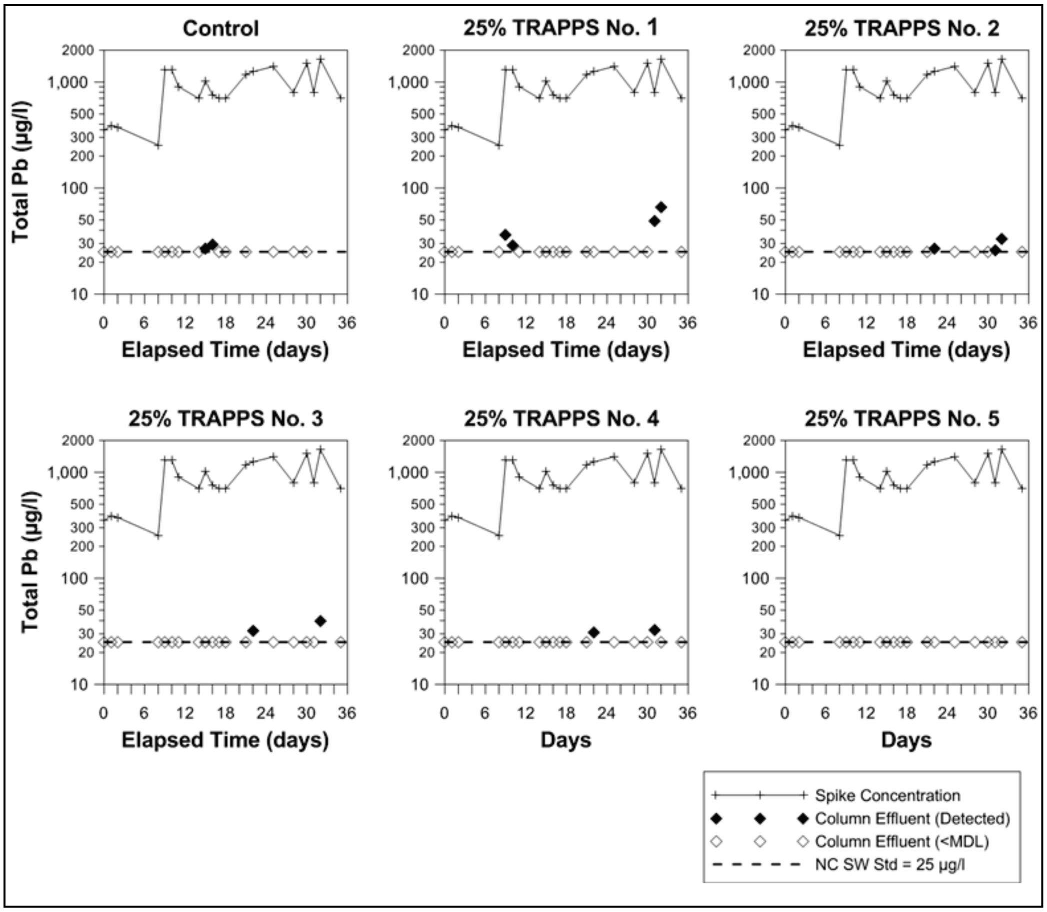
1.1.3 Proof-of-Concept study

A preliminary column study examined one site soil treated with various concentrations of the TRAPPS™ Pb stabilization amendment. Pb-contaminated soil was obtained from a skeet range in North Carolina (NC). A Pb solution of approximately 250-µg Pb/L was added to the columns weekly and the leachate collected and analyzed for heavy metals by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

Figure 5 shows the average leachate Pb concentration over 36 days from the columns (n=3). The untreated control had some leachate Pb concentrations that exceeded the NC surface water standard. At a 25 percent loading rate, the TRAPPS™ amendment (Formulation 5) maintained the Pb concentration below the NC surface water standard, which was used as the performance objective for that study.

Following the column study, the geotextile filter socks were studied on a larger scale in mesoscale rainfall lysimeters filled with skeet range soil. The socks were filled with sand amended with TRAPPS™#5 and/or processed fishbones each at varying concentrations. The filled socks were laid on the soil in the lysimeter. The lysimeter rain event used water with a similar Pb concentration as the column study. Leachate and runoff water were collected and analyzed for heavy metals by ICP-AES. Figure 6 compares the soluble and particulate Pb concentrations in the runoff water from a sock filled with sand (control) and one filled with sand and a 15 percent TRAPPS™#5 amendment.

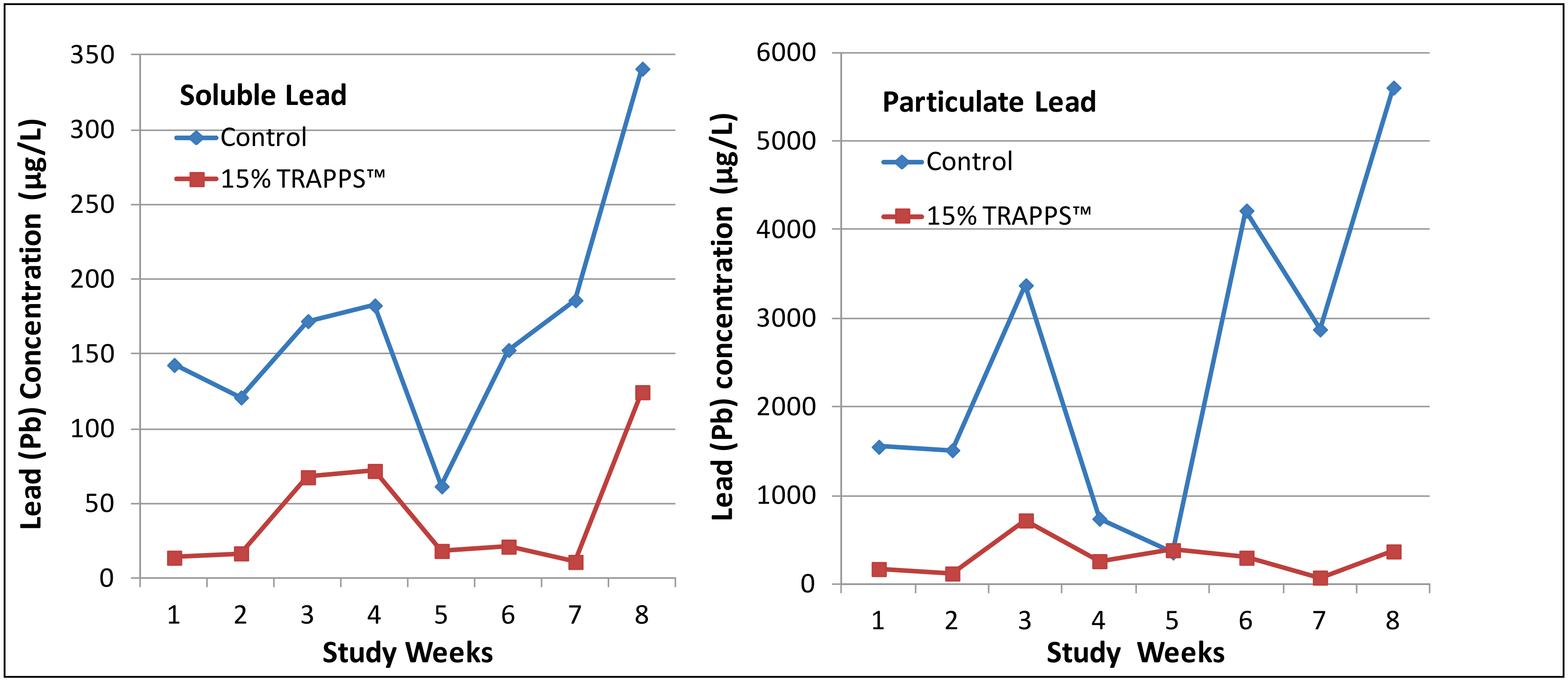
Figure 5. Lead concentration (ppb, µg/L) from soil amended with TRAPPS™ formulations at different concentrations.



As seen in Figure 6, the filter sock using sand amended with 15 percent TRAPPS™#5 reduced the concentration of dissolved Pb in the runoff water by 60 percent or more, relative to the control cells. The concentration of particulate Pb was typically reduced by an order of magnitude.

Given the large watershed areas that need to be protected and the high cost to install and maintain most runoff water management BMPs for metals, the low-cost, easy-to-use filter socks may offer a solution to improving the quality of surface receiving waters located adjacent to training ranges. At the end of its life cycle, the sock filler can be recycled to remove the metals, transported to a landfill, or potentially be left in place. The reduction in waste will translate into reduced hazardous waste landfill costs. Combining the filter sock geotextile with amendments for metal immobilization creates a containment system for metals found in surface water runoff from training ranges that is flexible, transportable, inexpensive, and easy to replace.

Figure 6. Soluble and particulate lead concentrations (µg/L) in runoff water following treatment with a filter sock filled with sand amended with 15 percent TRAPPS™.



1.1.4 Model of TSS removal by sand filters

Dortch (2013) developed a mathematical model to predict the performance and TSS removal characteristics of sand filter socks, such as the flexible reactive barrier. The model included the effects of TSS clogging in the socks over time. The intended use of the model is for site-specific design of the filters prior to construction and implementation. This model was used to provide design information and predict filter performance for surface runoff water at Fort Jackson, SC and Fort Leavenworth, KS; two potential field demonstration sites.

Due to the relatively low flow velocities through the porous media of the sand filters, the model assumes laminar flow through the sock; therefore, it is based on Darcy's law, which states:

$$v = K\frac{H_L}{L_f}$$

where,

v = superficial (Darcy) velocity of flow through the filter, m/hr
K = saturated hydraulic conductivity of the filter, m/hr
H_L = head loss of flow through the filter, m
L_f = thickness or length of flow path of the filter, m

The Darcy velocity is the same as the approach velocity, which is

$$v = \frac{Q}{W_c h}$$

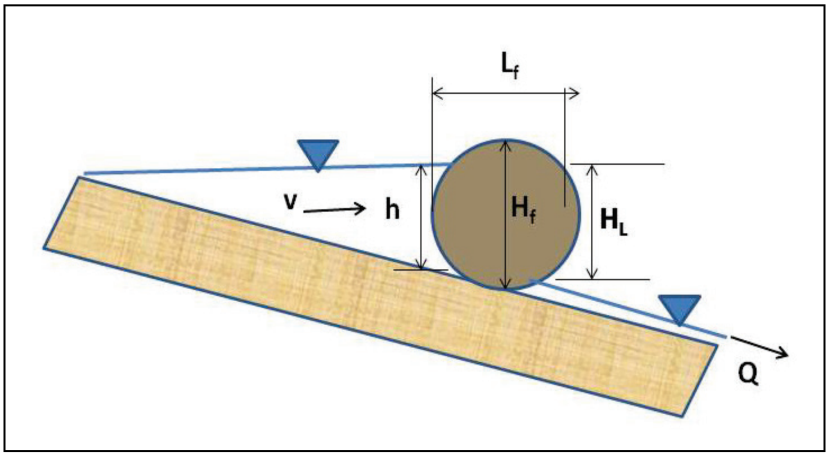
where,

Q = water flow rate through the filter, m^3/hr
W_c = width of the effective drainage approach channel (same as the filter width), m
h = water depth immediately upstream of the filter, m

The primary hydraulic features of sand filter socks are shown in Figure 7, where,

v = superficial (Darcy) velocity of flow through the sock, m/hr
K = saturated hydraulic conductivity of the sock, m/hr
H_f = height, i.e., diameter, of the sock, m
H_L = head loss of flow through the sock, m
L_f = thickness or length of flow path of the sock, m
Q = water flow rate through the sock, m^3/hr, and
H = water depth immediately upstream of the sock.

Figure 7. Flow schematic of the flexible reactive berm.



The model computes the water depth, flow rate, effluent TSS concentration, and filter characteristics (i.e., TSS removal coefficient, satuated hydraulic conductivity, and trapped sediment) versus time for a design storm event. The model also estimates effective filter sock life associated with sediment clogging.

1.2 Objectives

The treatability study objectives were to:

- Evaluate reactive materials that will adsorb soluble munitions metals including Pb, Zn, Cu, and Sb from solution.
- Assemble the reactive materials into a barrier similar to a soil erosion control sock, and perform a pilot-scale comparison of the most promising amendments and geotextiles.

2 Materials and Methods

2.1 Amendments

The amendments evaluated were TRAPPS™ 1, TRAPPS™ 2, and 3-step treated fishbone (BBB), or 3B fishbone. The TRAPPS™ amendments are a proprietary blend produced by Slater (UK) Limited that contain various concentrations of iron and manganese oxides. TRAPPS™ 1 is Formulation No. 281009 #2. TRAPPS™ 2 is Formulation No. 050405 #5. Each amendment was mixed with well-graded sand to achieve the appropriate amendment concentration (i.e., 1%, 5%, or 10%). Unamended sand and distilled, deionized (DDI) water were the experimental controls.

2.2 Soils

A comparison of the potential field demonstration site soil characteristics is provided in Table 2.

Table 2. Soil characterization

Parameter	Site Soils		
	Ft. Leonard Wood (MO)	Ft. Jackson (SC)	Ft. Leavenworth (KS)
Soil type	Sandy Silt with Gravel (ML)	Silty Sand (SM)	Sandy Clay (CL)
% Fines	50.7	22.3	67.5
% Sand	42.7	77.2	22.6
% Gravel	6.6	0.5	9.9
Specific gravity	2.77	2.62	2.70

Uncontaminated Silty Sand soil from Fort Jackson also provided a background metal analysis (Table 3). The USEPA considers metal concentrations in soil to be the concentration obtained following a total digestion (i.e., Method 3050b, or other) of the soil fraction that passes through a 1.7-mm sieve. This is a result of the often particulate nature of metals contamination. Seiving also avoids the digestion of large metallic particles like intact bullets. This uncontaminated Silty Sand soil has metal concentrations within normal ranges for the contiguous United States (Shacklette and Boerngen 1984).

Table 3. Background concentration of metals in uncontaminated Silty Sand soil from the Fort Jackson, SC, area, mean background metals concentrations of U.S. soils and background concentration range of metals in typical Eastern U.S. soil

Metal	Fort Jackson area concentration of uncontaminated bulk soil (mg/kg, dry weight)	Mean background concentration for US soils[a]	Typical Eastern US background levels[b]
Copper (Cu)	20.0	17	Not analyzed
Iron (Fe)	15,600	18,000	2,000 – 550,000
Manganese (Mn)	284	330	Not analyzed
Nickel (Ni)	18.5	13	0.5 – 25[c]
Lead (Pb)	16.3	16	4 – 61[d]
Antimony (Sb)	<0.600	0.52	<1.0 – 8.8
Zinc (Zn)	34.5	48	9-50

[a] Shacklette and Boerngen (1984).

[b] O'Toole (1994).

[c] New York State background.

[d] Average levels in undeveloped, rural areas.

Table 4 shows the concentration of munitions metals in the Silty Sand soil taken from a SAFR berm. After firing on the soil, the concentration of Pb increased from 16 mg/kg to 5,924 mg/kg ± 2,362 mg/kg. The concentration of Sb increased from <0.60 mg/kg to 139 ± 52 mg/kg. The concentration of Cu also increased significantly from 20 mg/kg to 310 mg/kg. Even with the large number of replicates (9), the large mass of each individual soil sample (600 to 800 g), 12 splitting and recombining steps, and sieving through a 1.7 mm sieve to remove particulate metals, the standard deviations are, in some cases, quite large. This is due to the particulate nature of certain metals, such as Pb, Cu, and Zn, as well as the heterogeneous distribution of munitions metals in firing range soils.

Table 4. Concentration of metals (mg/kg) in the contaminated Silty Sand soil from the area of Fort Jackson, SC following small arms firing

Metal	Average concentration (mg/kg)	Standard deviation (n=9)
Cu	310.22	136.71
Fe	5,506.67	333.35
Mn	85.94	5.54
Ni	6.67	0.46
Pb	5,924.44	2,361.90
Sb	139.27	52.03
Zn	42.38	12.83

2.3 Batch Adsorption Study

The method for determination of the 24-hr partition coefficient (K_d) for heavy metals in soils is based on Appendix 6 of the USEPA report (1999b), “Understanding Variations in Partition Coefficient, K_d, Values”. Batch sorption studies evaluated the sand and the amendments for effectiveness at adsorption of munitions metals from solution. Each experiment was run in triplicate. Single metal stock solutions were prepared for Pb, Cu, Sb, Zn, Cd, and Cr (Table 5). Each metal was evaluated at six concentrations in order to provide a linear isotherm for K_d calculation.

Table 5. Stock solutions of metals for determination of the 24-hr partition coefficient in sand and amendments

Metal	Stock solution concentration (mg/L)					
Pb	350	360	370	380	390	400
Cu	100	110	120	130	140	150
Zn	50	60	70	80	90	100
Sb	50	60	70	80	90	100
Cd	50	60	70	80	90	100
Cr	50	60	70	80	90	100

2.4 Column Studies

Columns were prepared for the leaching study (Figure 8) using the three site soils. Control columns were prepared with clean, graded sand. A stock solution of each metal at 50 mg/L and 100 mg/L was prepared and solutions were added to the columns weekly. The leachate was collected after a 24-hr period. Columns were run in triplicate. Data collected included leachate metal concentrations and TSS.

2.5 Batch Leaching Tests

At the conclusion of the column study, the sand/amendments were removed from each column. Metal leaching following the treatments was measured using:

- Toxicity Characteristic Leaching Procedure (TCLP),
- Synthetic Precipitation Leaching Procedure (SPLP), and
- Distilled, Deionized Water Suspend and Settle (DDI S&S) tests.

This allowed an estimate of the longevity, and the potential for non-hazardous disposal, of the filter sock sand/amendments.

Figure 8. Photograph of column assembly and leachate collection.

2.5.1 Toxicity Characteristic Leaching Procedure (TCLP)

Following USEPA SW 846 Method 1311 (1999a), the TCLP test was performed on the column soils to determine the leaching potential of the munitions-contaminated soils. A 1:20 weight to volume (w:v), soil-to-extraction solution ratio was used. The soil extractions were placed on a tumbler for 18 ± 2 hours. After tumbling, an aliquot of the sample was removed, centrifuged, and then 60 mL of sample was filtered through a 0.45-µm syringe filter and analyzed for munitions metals.

2.5.2 Synthetic Precipitate Leaching Procedure (SPLP)

Following USEPA SW 846 Method 1312 (1999a), the SPLP test was performed on the column soils to determine the leaching potential of the munitions-contaminated soils. A 1:20 (w:v) soil-to-extraction solution ratio was used. The soil extractions were placed on a tumbler for 18 ± 2 hours. After tumbling, an aliquot of the sample was removed, centrifuged, and then 60 mL of sample was filtered through a 0.45-µm syringe filter and analyzed for munitions metals.

The SPLP differs from the TCLP in the use of different extraction fluids. The SPLP is designed to simulate the leaching effects from material sitting on the surface of the ground and exposed to weathering, with the assumption that the precipitation is slightly acidic.

2.5.3 Distilled, Deionized Water Suspend and Settle (DDI S&S) Leaching Procedure

The DDI S&S procedure is a water-leaching test; a modification of the TCLP procedure. An amended soil to DDI water ratio of 1:20 (w:v) was maintained, similar to the TCLP procedures. The samples were placed on a shaker table for 1 hour then allowed to settle for 18 ± 2 hours. After settling, aliquot samples were removed, filtered, and analyzed for munitions metals. The test differs from the TCLP and the SPLP by using extraction fluids at circumneutral pH.

2.6 Lysimeter Evaluation

2.6.1 Column Lysimeter

The column lysimeter study was conducted using the Sandy Clay soil from Fort Leavenworth, described in Table 2, to study the interaction between the sand/amendments, the soil, metals, and TSS. A schematic of the column lysimeter is shown in Figure 9. Large diameter, clear PVC columns were used, and the geotextile was cut into a disc the size of the inner diameter of the column. The well-mixed sand/amendment was placed on top of the bottom disc to a depth of 10 cm. A second disc of geotextile was placed on top of the sand. Contaminated soil was sieved and analyzed to establish an initial metals concentration. One Kg of the sieved fines was used to amend the solution added to the column. The input liquid contained 50 µg of Pb per mg of suspended solids. The solution was agitated in order to simulate movement of suspended solids with surface stormwater. The solution was allowed to move through the simulated sock under gravity. Leachate samples were collected and analyzed for total and dissolved metals, phosphorus, nitrate/nitrite, TSS, and pH.

2.6.2 Mesoscale Rainfall Lysimeter

The mesoscale rainfall lysimeter study was conducted using the Silty Sand soil of Fort Jackson, SC, described in Table 2, 3, and 4. The lysimeter (Figure 10) was assembled as described in Larson et al. (2004, 2005, 2007a). The soil was artificially weathered through 16 rain events, which simulated 1.3 years of exposure. Leachate and runoff water were collected following each rain event. The waters were measured to calculate total pore volume and metal mass balances and analyzed for total and dissolved metals.

Figure 9. Schematic of column used to examine the interaction between sand/amendments, metals, and soil types.

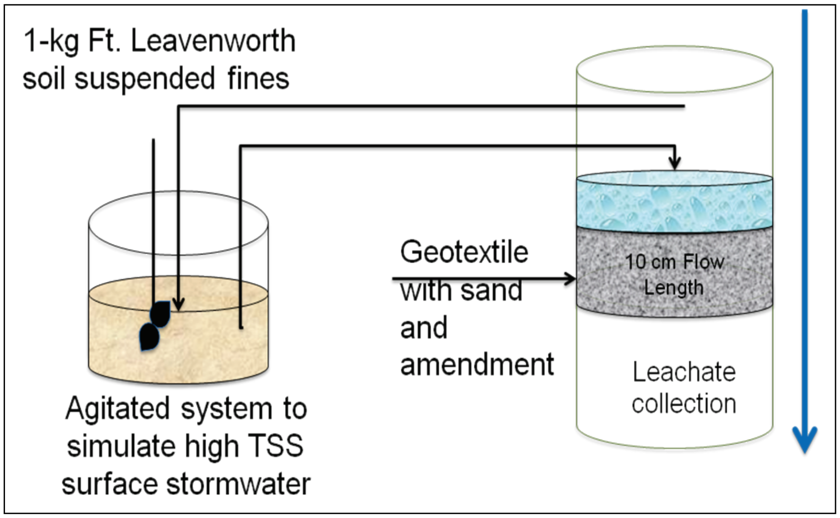
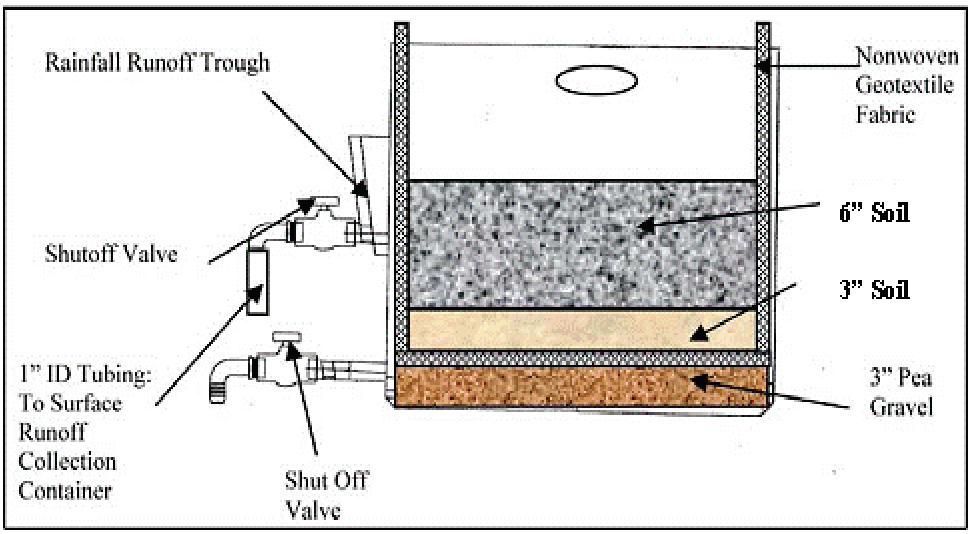


Figure 10. Cross section of mesoscale rainfall lysimeter.



2.7 Model Application

The sand filter sock performance model (Dortch 2013) was applied to two SAFRs: Range 9 at Fort Jackson, SC and Kinder Range at Fort Leavenworth, KS. The details of these two applications are presented in Appendices A and B. The model was used to assess sand filter sock performance for a design storm. Performance measurements consisted of required filter sock diameter and length to avoid water over-topping for the design storm and estimate of filter sock life due to sediment clogging. Other measurements included TSS removal, mass of sediment trapped, change in the filter sock removal coefficient, and saturated hydraulic conductivity for the design storm.

The model was developed for a sand filter sock material, thus, there are accuracy limitations associated with application to the flexible reactive filter sock barriers featured in this study. The amendments added to sand may affect filter sock characteristics, such as the porosity, average grain size, initial TSS removal coefficient, and sediment clogging coefficients.

2.8 Analysis Methods

Methods of sample analysis are summarized in Table 6. The metal concentrations from both liquid and solid samples were determined by ICP-AES on an Optima 4300 dual view (Perkin-Elmer, USA). The detection limit for metals in water was 0.05 mg/L. In soil, the detection limit for metals was 0.5 mg/Kg. TSS was analyzed spectrophotometrically using Method SM 2540D and a Hach DR/200 spectrophotometer read at 810 nm. Nutrients were analyzed using ion chromatography (IC) (Thermo Scientific Dionex). Negatively charged compounds, such as nitrate and nitrite, were quantified using an AS-11HC resin column (Thermo Fisher Scientific), 0.400 mL/min isocratic mobile phase of 25 mM hydroxide, and conductivity detection. Positively charged compounds, such as phosphate, were quantified using a CS16 cation-exchange column (Thermo Fisher Scientific), 0.500 mL/min isocratic mobile phase of 30 mM methanesulfonic acid, and conductivity detection.

Table 6. Analysis methods for solids and liquids

Analysis	Method
Soils/amendments	
Metals	SW-846 Method 3051[a]
pH	SW-846 9045 (electrode)
TCLP	SW-846 Method 1311 [a]
SPLP	SW-846 Method 1312 [a]
DDI S&S	SW-846 Method 1311 - modified [a]
K_d	US EPA (1999b)
Aqueous (Leachate and Runoff Water)	
Total metals	SW-846 3015
Dissolved metals	SW-846 3015/3051
pH	SW-846 9040C (electrode)
Total suspended solids (TSS)	Method SM 2540D (spectrophotometer)[b]
Phosphate	Dionex ICS-2500 (ion chromatography)
Nitrate/nitrite	Dionex ICS-2500 (ion chromatography)

[a] USEPA (1999a)

[b] American Public Health Association (1998)

3 Results and Discussion

3.1 Batch Adsorption Studies

The data generated from the sorption K_d experiments yielded adsorption isotherms for each experimental amendment and the individual heavy metals used. Amendment metal concentration was obtained by subtracting the concentration of metal in solution at each sampling period from the total mass of metal added to the system. While filtering is a possible source of metal loss, standard procedure for K_d determination using the batch method involves analysis of a filtered solution. The material retained on the filter is defined as insoluble material (USEPA 1999b).

A summary of the results of a linear fit determination of sorption K_d, using a section of the curve in the linear region (per K_d discussion in USEPA 1999b), is provided in Tables 7, 8, and 9 for the amendments TRAPPS™ 1, TRAPPS™ 2, and the 3B fishbone, respectively. When necessary, a least squares fit was performed using selected points in the linear portion of the isotherm to produce a K_d value that is valid for the entire concentration range as shown in Figures 11 and 12 for the 5 percent TRAPPS™ and the 5 percent 3B fishbone. The 3B fishbone functionalized with nano-Zero Valent Iron (nZVI) did not prove to be an improvement over the unfunctionalized fishbone; and due to cost, its evaluation was discontinued.

Table 7. Summary of linear K_d data for the experimental amendment TRAPPS™ 1 at different concentrations and four munitions metals.

Amendment Concentration (mg/L)	K_d Parameter	Metal			
		Pb	Cu	Zn	Sb
1%	K_d	293.5	20.2	32.3	61.2
	R^2	*0.9625*	*0.8886*	*0.8975*	*0.9423*
5%	K_d	ND	167.1	55.0	259.7
	R^2	*NA*	*0.8779*	*0.9030*	*0.9379*
10%	K_d	ND	6484.2	82.6	474.8
	R^2	*NA*	*0.9436*	*0.9459*	*0.9445*

ND= not detected/complete sorption

NA=not applicable

Table 8. Summary of linear K_d data for the experimental amendment TRAPPS™ 2 at different concentrations and four munitions metals.

Amendment Concentration	K_d (Parameter)	Metal			
		Pb	Cu	Zn	Sb
1%	K_d	45.62	3.48	ND	ND
	R^2	*0.9712*	*0.5326*	*NA*	*NA*
5%	K_d	643.05	5.98	3.64	11.19
	R^2	*0.7460*	*0.8130*	*0.9463*	*0.9175*
10%	K_d	9,254.96	3.46	25.34	12.45
	R^2	*0.9128*	*0.9765*	*0.8341*	*0.9066*

ND= not detected/complete sorption

NA=not applicable

Table 9. Summary of linear K_d data for the experimental amendment 3B fishbone at different concentrations and four munitions metals

Amendment Concentration	K_d (Parameter)	Metal			
		Pb	Cu	Zn	Sb
1%	K_d	10,284.90	871.12	66.19	ND
	R^2	*0.3875*	*0.9643*	*0.8692*	*NA*
5%	K_d	6,813.92	109.34	53.99	ND
	R^2	*0.3838*	*0.8808*	*0.9952*	*NA*
10%	K_d	3,525.84	30.87	46.52	27.34
	R^2	*0.9651*	*0.9915*	*0.9802*	*0.9302*

ND= not detected/complete sorption

NA=not applicable

Figure 11. Linear K_d of 5% TRAPPS™ amendment with four metals.

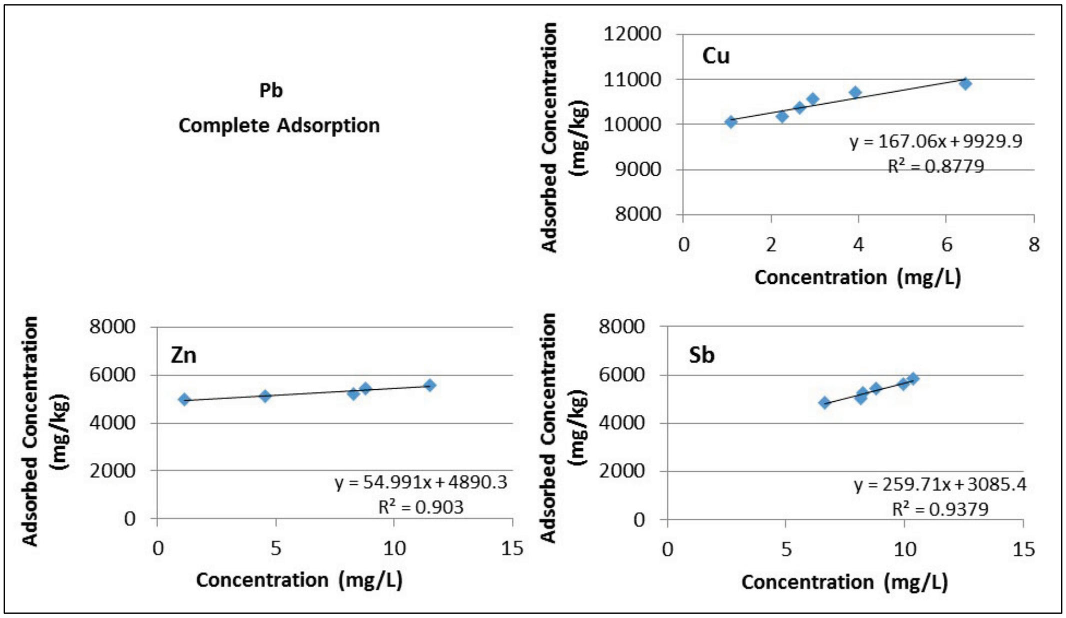
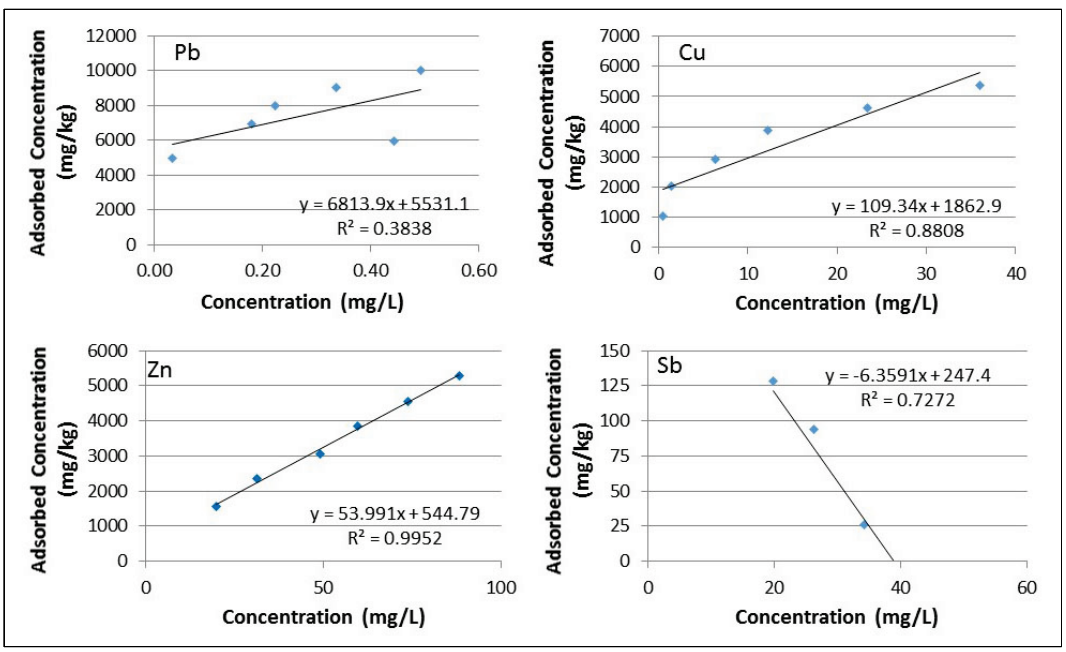


Figure 12. Linear K_d of 5% 3B fishbone and four metals.



A summary of the Kd data for each metal at each concentration of each amendment is shown in Table 10. As seen, the oxides absorb Pb completely at five percent loading rate and adsorb Cu and Zn even at one percent amendment. The biogenic apatite absorbs Sb well at either the one percent or five percent loading rates.

Table 10. Summary K_d data by metal and amendment

Metal	Amendment	1%	5%	10%
Pb	FeMn-oxide	294	ND	ND
Cu		20	167	6,484
Zn		32	55	82
Sb		61	260	475
Pb	Processed fishbone (biogenic $CaPO_4$)	10,285	6,814	3,526
Cu		871	109	31
Zn		66	54	47
Sb		ND	ND	27

ND = not detected/complete adsorption

3.2 Column Study

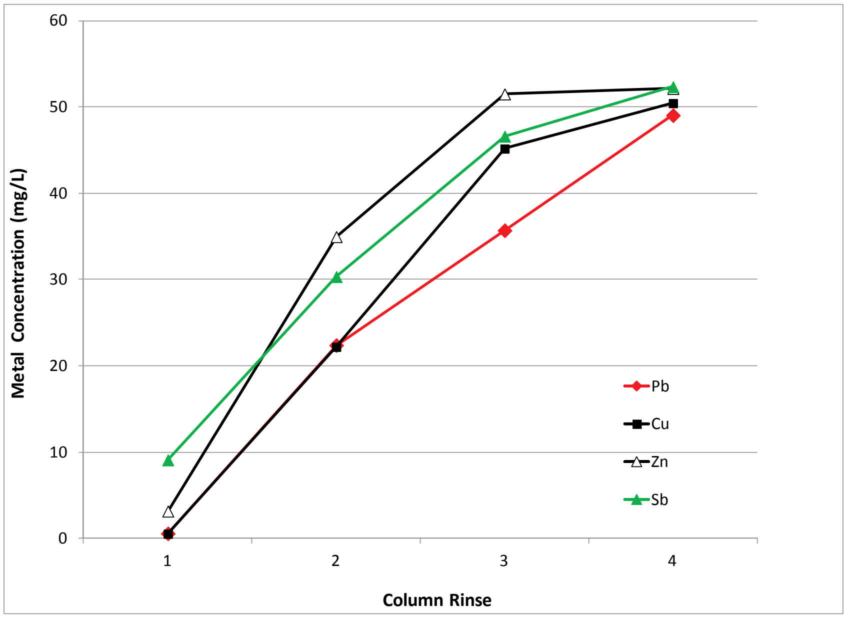
3.2.1 Sediment and Metal Leaching

As described in Section 2.4, a stock solution of each metal at 50 mg/L and 100 mg/L was prepared and solutions were added to the columns weekly. Leachate was collected at 24-hrs. Metal leaching from the control (sand) is shown in Figure 13 and compared to other soil types in Table 11. Lead and Sb concentrations are shown in Figure 13 as red and green lines, respectively. Leachate from sand demonstrated consistent release of increasing concentrations of metals over time.

Table 11. Metal leaching from three soil types through successive rinses.

Metal	Soil type	Metal concentration in leachate (mg/L)					
		Initial	Rinse 1	Rinse 2	Rinse 3	Rinse 4	Rinse 5
Pb	Sand	50	1	22	36	49	
Cu			1	22	45	50	
Zn			3	35	52	52	
Sb			9	30	47	52	
Pb	Silty Sand (22% fines)	100	ND	ND	5	7	12
Cu			ND	2	5	10	14
Zn			3	6	15	24	32
Sb		50	1	6	12	14	19
Pb	Sandy Silt with gravel (51% fines)	100	2	12	22	39	48
Cu			1	8	14	20	31
Zn			4	10	14	23	30
Sb		50	3	9	24	36	44

Figure 13. Concentration of leachate metals over four rinses through a sand (control) column.



Release of TSS from three soil types over time is shown in Table 12. Sand had the lowest TSS release. The Silty Sand released suspended solids early, then decreased over time. The Sandy Silt with gravel maintained a relatively constant release over time. The NPDES permit regulations under 40 CFR 122 are a maximum of 60 mg/L of TSS for any one day, and the monthly average release shall not exceed 31.0 mg/L. If state water quality standards exceed those of the federal government, then the state standards will apply. The three soils examined here did not exceed the 60 mg/L daily limit in the first four weekly leaching events. Also, none of the soils exceeded the monthly average release for TSS, although total release was highest from the Silty Sand.

Table 12. Total suspended solids (mg/L) leached from three soil types in weekly rinses totaling one month.

Soil type	TSS concentration (mg/L) in leachate weekly					
	1	2	3	4	Total	Avg (month)
Sand	1.33	1.67	2.00	1.67	6.67	1.67
Silty Sand (22% fines)	25.67	35.67	6.33	5.00	72.67	18.17
Sandy Silt with gravel (51% fines)	9.33	7.00	8.00	10.00	34.33	8.58

3.2.2 Post Treatment Metal Leaching

Metal leaching from the amendments following the treatments was measured using the TCLP, the SPLP, and the DDI S&S leaching tests. This allowed an estimate of the longevity of the treatment and the potential for non-hazardous disposal of the filter socks. The initial concentrations of each stock solution are listed in Table 13. The results of the leaching tests are discussed in the following sections.

Table 13. Initial metal concentration (mg/L) of leaching solutions.

Metal	Concentration (mg/L)
Pb	246
Cu	211
Zn	196
Sb	220

3.2.2.1 TCLP

The TCLP regulatory limit for Pb is 5 mg/L. Metal leaching from the control and contaminated Silty Sand soil is presented in Table 14. Concentrations highlighted in green are above the established TCLP regulatory limit for that metal. Regulatory limits for many of the other metals have not been established. A common assessment of potential toxicity is the “Rule of 20”. If the leachate concentration is 20x the TCLP limit, then the waste may be considered hazardous. One drawback to this test is the limited number of metals with established TCLP limits.

Table 14. Metal concentration (mg/L), obtained by TCLP extraction of control Silty Sand soil and SAFR berm soil fired on with lead ammunition.

Metal	Concentration (mg/L) of metal in TCLP solution	
	Control Silty Sand soil	Silty Sand SAFR soil
Pb	1.34 ± 0.09	482.67 ± 76.17
Cu	0.28 ± 0.01	6.26 ± 1.28
Zn	<0.10	1.37 ± 0.12
Sb	<0.03	1.76 ± 0.24

Biogenic apatite was included as an amendment in the filter sock because it kept all regulated metals below their permitted TCLP concentrations (Table 15).

Table 15. Metal concentration (mg/L) obtained by TCLP extraction of sand (control) and amendments.

Metal	Concentration (mg/L) by amendment			
	Sand	Biogenic apatite	TRAPPS™ 1	TRAPPS™ 2
Pb*	4.40 ± 0.53	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Cu	4.87 ± 0.31	1.18 ± 0.13	0.21 ± 0.03	1.76 ± 0.10
Zn	3.81 ± 0.22	1.64 ± 0.48	0.77 ± 0.06	6.56 ± 0.95
Sb	3.12 ± 0.41	1.37 ± 0.14	0.25 ± 0.11	4.11 ± 0.69

*Regulated metal

3.2.2.2 SPLP

The SPLP is the leach test used to assess the potential impact to groundwater or surface water when soil is exposed to normal weathering and a slightly acidic rainfall. Results of leaching from the control and the amendments under conditions of the SPLP procedure are shown in Table 16.

Table 16. Metal concentration (mg/L) obtained by SPLP extraction of sand (control) and amendments.

Metal	Concentration (mg/L) by amendment			
	Sand	Biogenic apatite	TRAPPS™ 1	TRAPPS™ 2
Pb*	4.03 ± 0.13	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Cu	3.70 ± 0.15	0.78 ± 0.07	0.00 ± 0.00	0.00 ± 0.00
Zn	4.07 ± 0.27	0.30 ± 0.05	0.00 ± 0.00	0.84 ± 0.10
Sb	3.02 ± 0.13	3.64 ± 0.51	0.16 ± 0.04	2.67 ± 0.48

*Regulated metal

3.2.2.3 DDI S&S

DDI S&S is the most universal of the laboratory evaluation techniques, as it involves only the soil sample and distilled water. A limitation of the TCLP and SPLP procedures is that they were designed to produce accelerated dissolution via reduced pH for metal species such as oxides of Pb and Cu that exhibit increased solubility at a lower pH. DDI S&S leaching tests were done in order to evaluate the potential for metals in range soils to partition into water that could leave the range area via leaching or surface water runoff. Results of metal leaching from the control and amendments under conditions of the DDI S&S procedure are shown in Table 17.

Table 17. Metal concentrations (mg/L) following DDI S&S leach testing from sand (control) and amendments.

Metal	Concentration (STDEV)			
	Sand	Biogenic apatite	TRAPPS™ 1	TRAPPS™ 2
Pb	1.60 (0.17)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Cu	4.17 (0.52)	0.52 (0.00)	0.00 (0.00)	0.00 (0.00)
Zn	1.74 (0.11)	0.23 (0.00)	0.00 (0.00)	0.49 (0.03)
Sb	3.56 (0.46)	4.07 (0.03)	0.18 (0.39)	2.77 (0.42)

The uncontaminated Silty Sand site soil showed no significant metal leaching with the DDI S&S procedure (data not shown). However, as seen in Table 18, the same soil type from a SAFR berm showed significant DDI S&S metal leaching, particularly of Pb.

Table 18. Metal concentrations (mg/L) in DDI S&S leachates from Silty Sand soil used as a SAFR berm.

Metal	Concentration (mg/L)	STDEV
Pb	3.12	0.35
Cu	0.28	0.03
Zn	0.07	0.01
Sb	0.20	0.02

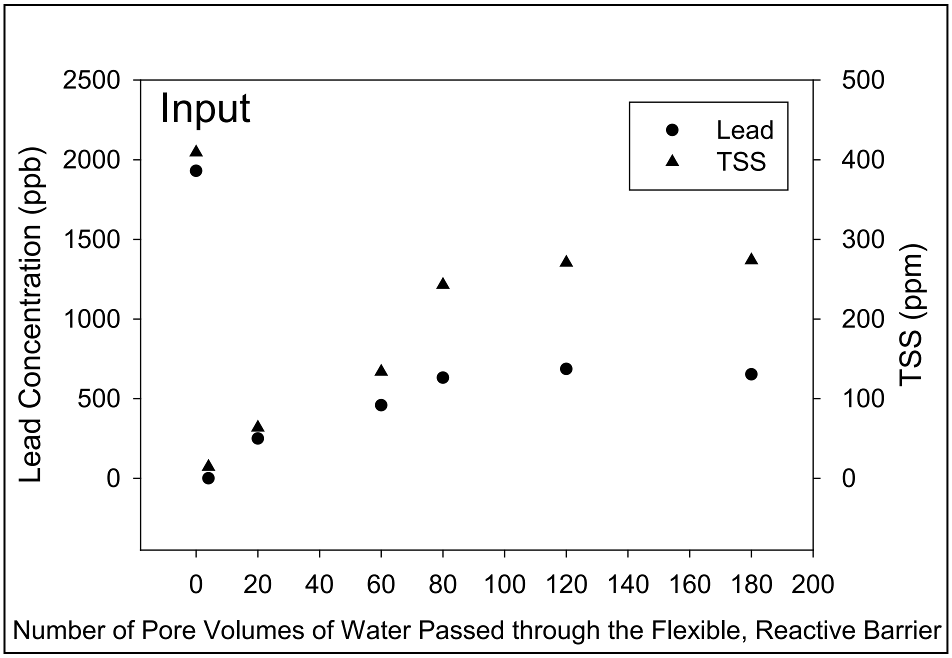
3.3 Lysimeter Evaluation

3.3.1 Column lysimeter

In the column lysimeter (Figure 14), the Pb input was 50 µg Pb / mg of suspended solids. The Pb output was 20 µg Pb / mg of suspended solids, a 60 percent mass transfer to the amendments over a 10 cm flow length. After filtering through over 100 cm of reactive filter sock material, a Pb reduction of 98 percent is achievable with a slow clogging rate.

The initial concentration of TSS was 400 mg/L. At one pore volume, this was reduced to 0 mg/L, or non-detectable. At 20 pore volumes, TSS release increased to 50 mg/L. The releases increased with pore volumes until 80 pore volumes had passed through the reactive filter sock material. At this volume, they held steady at 290 mg/L TSS. These values show that the reactive barrier clogged slowly, and there was a close association with the Pb release rate through the first 60 pore volumes of water.

Figure 14. Relationship of Pb output and TSS concentration in the flexible reactive barrier.



3.3.2 Mesoscale Rainfall Lysimeter

The larger scale rainfall lysimeter tests showed no significant leaching of dissolved lead (<0.45-microns) from the Silty Sand soil in either leachate or runoff water over the 16 weekly rain events (data not shown).

The total Pb concentration in leachate and runoff water from the lysimeters over the 16 weeks is shown in Table 19. The average Pb concentration in leachate from the Silty Sand soil was 0.06 mg/L. The highest single leachate value for Pb was 2.02×10^{-3} g. The total mass of Pb leached was 1.08×10^{-2} g. Compared to the concentrations of Pb detected in the leachate, relatively larger amounts of Pb were found in the runoff water; average 0.22-mg/L, 8.09×10^{-3} g was the single highest value, and 2.24×10^{-2} g was the total mass of Pb in the runoff water.

Table 19. Total lead concentration (mg/L) in leachates and runoff water from the Silty Sand soil over 16 rain events (a simulated rainfall of 1.3 years).

Weekly rain event	Concentration of Total Lead (mg/L)	
	Leachate	Runoff
1	<0.05	0.28
2	<0.05	0.19
3	<0.05	<0.05
4	<0.05	<0.05
5	<0.05	<0.05
6	<0.05	0.72
7	0.15	0.87
8	0.19	0.29
9	<0.05	0.06
10	<0.05	0.10
11	<0.05	0.10
12	<0.05	0.09
13	<0.05	0.11
14	<0.05	0.11
15	<0.05	0.07
16	<0.05	<0.05

4 Conclusions

Laboratory lysimeter studies showed that runoff water is a significant pathway for migration of lead, and other heavy metals, from various soil types. The lead is highly associated with the soil particles making up the TSS released from each soil.

After evaluation of the data, the socks for the field demonstration will be constructed using a non-woven geotextile filled with well-graded sand amended with a combination of the FeMn-oxides (TRAPPS™ 1) and processed fishbone, each at a five percent loading rate.

At the end of useful life, the FRBerms can potentially be disposed of as non-hazardous waste. At bench-scale, the use of biogenic apatite as one of the sand amendments allowed the sorptive material to pass the TCLP test for landfill disposal. This result will be evaluated at field-scale.

The mathematical model of sand filter sock performance was used to estimate filter sock size requirements and estimated filter sock life for ranges at Fort Jackson, SC and Fort Leavenworth, KS as discussed in Appendices A and B. These results can be used to assist in designing and installing filters at these sites for field-testing.

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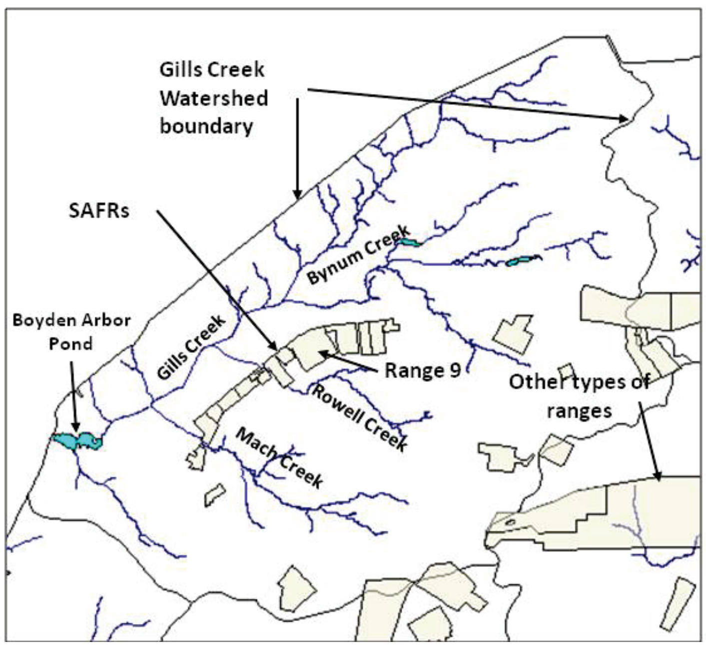
Appendix A: Case Study: Fort Jackson, SC

A.2 Background

Sand filter sock performance models (Dortch 2013) that have been developed for the Training Range Environmental Evaluation and Characterization System (TREECS), and which are available within the TREECS *Tools* menu, were applied to obtain preliminary design information for filter socks that would remove Pb and other metals in range runoff water for SAFRs at Fort Jackson, SC. The Fort Jackson SAFRs are located within the Gills Creek watershed, which drains into Boyden Arbor Pond as shown in Figure 15.

Figure 15. Gills Creek Watershed, Fort Jackson, SC.



There are two sand filter models, one for sand filter performance during design storms, and one for assessing filter effective life. Filter sock performance relates to depth of the water upstream of the sock relative to filter sock height. The intent is to design filter socks to avoid runoff water over-topping during the design storm. Other performance variables include filter sock flow rate, hydraulic conductivity, removal coefficient, and how these variables change during the design storm. Due to total suspended sediment (TSS) trapping, sand filters eventually become clogged rendering them ineffective for further TSS removal. The second model estimates the amount of time it takes for the clogging to occur. At this point, the filters should be replaced. Both models exist as Excel workbooks and are documented by Dortch (2013).

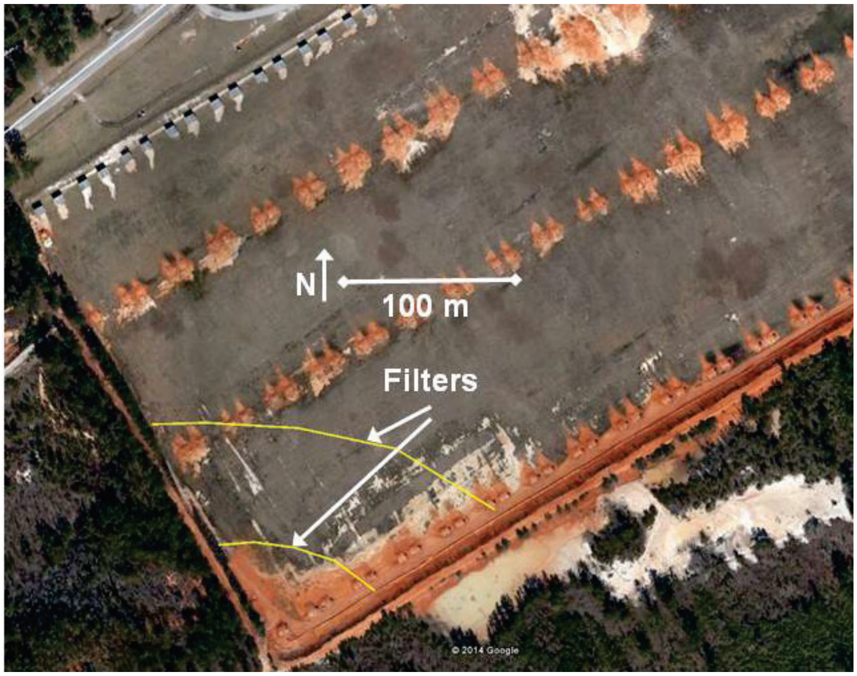
The sand filter models are planned for Range 9 of the SAFRs at Fort Jackson. Range 9, which is within the Rowell Creek sub-watershed (see Figure 15), has the highest firing rates of all of the SAFRs; and it is the largest of the 13 contiguous SAFRs in the Gills Creek Watershed. Thus, Range 9 is a good case study example of what can be required for filter socks. The model inputs and output results for filter socks on Range 9 are presented below. These results should help with developing filter socks for the other SAFRs. The prototype filter socks will contain a mixture of sand for filtration of particulate metals and other material for adsorbing dissolved metals. The sand filter models do not account for the properties of the adsorbing material, thus, the results presented here are representative for pure sand. Removal of TSS, which is a surrogate for particulate metals, is discussed, but performance for removal of dissolved metals is not included.

A.2 Model inputs

A Google Earth view of Range 9 is shown in Figure 16 with suggested filter sock locations denoted. The lengths of the two socks are 225 m and 105 m, and they are about 75 m apart, all of which are model inputs. Longer sock length reduces the required filter sock height, which helps to avoid over-topping of water flow. These filter placement locations were selected to take advantage of the ground elevation as determined from Google Earth. The ground elevation varies between about 255 and 257 ft. along the path of the longer filter sock and between about 253 and 255 ft. along the path of the shorter filter sock, with the lowest elevations near the middle of both sock paths. Some grading of the ground may be required to provide a level crest for the filter sock across the entire path, which would help ensure more evenly distributed flow through each filter sock.

The lowest elevations on this range are in the southeast corner of the range where there is a drainage culvert for the entire range. Thus, filter socks at the locations shown in Figure 16 should capture most of the runoff from the range before exiting the range and traversing to the receiving stream, Rowell Creek. The longer filter sock will trap most of the TSS in range runoff, and its longer length is required to reduce the required diameter of the filter sock to avoid over-topping.

Figure 16. Range 9 showing filter sock locations



The purpose of the shorter filter sock length is to capture catchment runoff downstream of the longer, upstream filter sock. If only the shorter filter sock is implemented, its shorter length will result in substantial over-topping. The upstream filter sock attenuates the runoff hydrograph resulting in a shorter length and/or diameter to avoid over-topping for the downstream filter sock.

Each filter sock will remove a large portion, if not all, of the TSS flowing into it until becoming clogged. After becoming clogged, the filter sock should be replaced with another like filter sock at the same location. The original sand filter model (Dortch 2013) was modified to allow varying approach flow width and filter sock length for each sock in a cascade of filter socks.

The diameter of both filter socks was assumed to be 18 inches (0.457 m). The filter sock size is an input that can be varied to handle various size storms without over-topping. Multiple sizes were tested, and a filter sock diameter of 18 inches was found to be mostly adequate for handling the 10-year, 24-hour storm for this part of South Carolina. This storm has a rainfall depth of 6 inches occurring over 24-hours and a recurrence or return interval of 10-years as depicted by the U.S. rainfall frequency atlas (USDC 1961).

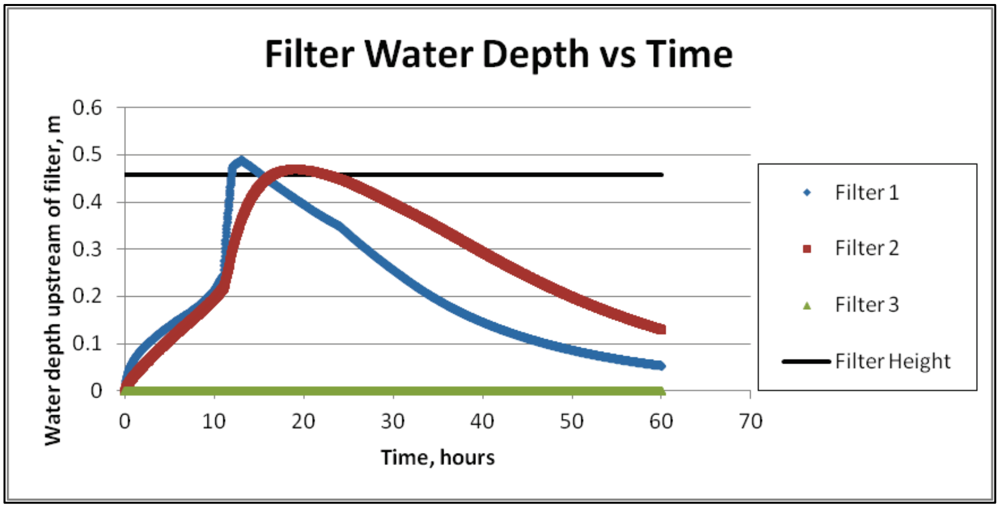
The effective sand grain size (d_{10}) of the sand was assumed to be 0.5 mm. This means that the median grain size of the sand is on the order of 1 mm, which is coarse sand. Finer sand can be used, but such will result in more water over-topping for this design storm and the need for greater filter sock diameter and/or lengths. Finer grain size causes lower hydraulic conductivity, which translates into greater water depth upstream of the filter sock. Other input parameters describing filter sock characteristics were set to default values, which included: sand particle shape factor (sphericity) = 0.9; sand initial porosity = 0.4; bulking factor of trapped sediment = 1.25; filter initial removal coefficient = 25 m^{-1}; filter clogging factor coefficient 1 = 125 m^{-1}; and filter sock clogging factor coefficient 2 = 400 m^{-1}. Dortch (2013) described all input parameters in his report.

Other required inputs for the Range 9 site included: rainfall catchment area = 160,000 m^2; rainfall depth = 6 inches; rainfall duration = 24-hours; storm type distribution = II; average annual rainfall = 45 inches; average number of days per year with significant rainfall (> 0.1 inches) = 115 days; *Rational Method* runoff coefficient = 0.4; ground slope = 0.005; water temperature = 18 degrees C; TSS specific gravity = 2.65; and TSS concentration in runoff = 100-mg/L. The TSS concentration of the runoff is a sensitive model input that greatly affects the effective filter sock life. ATC (2009) reported that the average TSS concentration of runoff from Range 9 is approximately 85 mg/L. However, these data included a TSS concentration of 500-mg/L.

A.3 Model results

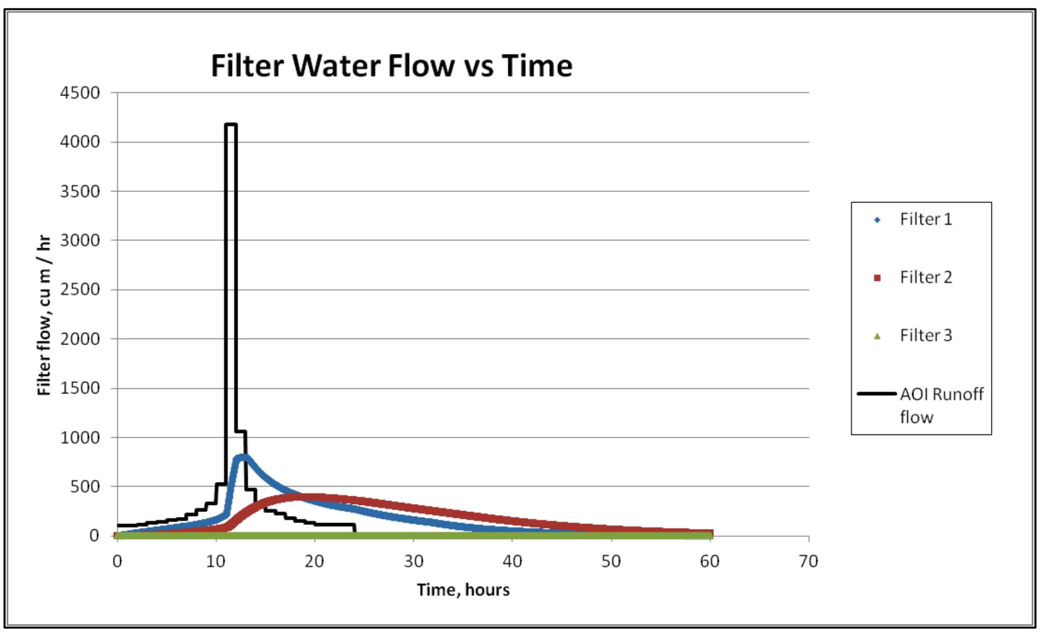
The model allows up to three filter socks, but only two were used here, so all output for the third sock shows up as zero values in output plots. Two filter socks were determined to be optimal for the range involved. The computed water depth of flow upstream of the filter socks versus time is plotted in Figure 17. The figure shows that the 10-year, 24-hour storm results in a water depth that slightly over-tops the upstream, longer filter sock, but does not over-top the downstream, shorter filter sock. More frequent storms should not over-top either filter sock. Storms of the same frequency but shorter duration exhibit peak depths that are about the same or slightly less than that shown in Figure 17, but the peak times are shifted to the left or earlier, and the areas under the depth curves are less.

Figure 17. Range 9 computed water depth versus time, immediately upstream of each filter sock.



The computed water flow rate versus time for the catchment area of interest (AOI) (i.e., range area runoff) and flow through each filter sock are plotted in Figure 18. This figure shows how the filter socks greatly attenuate the flow rate resulting in a much lower peak flow rate, but a longer duration of flow than the range runoff without the filter socks.

Figure 18. Range 9 computed water flow rate versus time for AOI and each filter sock.



The filter sock storm performance model also showed that the pore-water concentration of TSS trapped within the upstream filter sock peaked at about 150,000 mg/L at the end of the 60-hour simulation. At the end of the simulation, the total trapped TSS mass in the upstream filter sock was about 1,000 kg. The filter sock effluent TSS concentration was practically zero for both filter socks throughout the simulation; thus, for practical purposes, essentially all of the TSS in runoff was trapped. Most of the particulate metal concentration in runoff is expected to be trapped as well. Due to partial clogging, the hydraulic conductivity of the upstream filter sock decreased by half, from about 8 to 4 m/hr during the storm.

The pore-water concentration of TSS trapped within the downstream filter sock peaked at about 6,000 mg/L. At the end of the simulation, the total trapped TSS mass in the downstream filter sock was only about 24 kg. The downstream filter socks adsorb much less sediment because of the large amount of trapping provided by the upstream filter sock. Most of the sediment trapped in the downstream filter sock is associated with the incremental runoff that occurs between the two filter socks. The small amount of sediment trapping in the downstream filter sock resulted in very minor changes in the downstream filter sock characteristics (hydraulic conductivity and filter coefficient) due to little clogging.

The model for effective filter sock life predicted that the upstream range sock will become ineffective for removing TSS after about 9 to 10 months. It should be recognized that this estimate of life is an approximation based on average annual rainfall and TSS concentration in runoff. An unusually wet year with multiple large storms occurring within a season could reduce the effective life. Additionally, if the TSS concentration of the runoff is greater, the effective life is reduced. For example, if it is assumed that influent TSS concentration is 500 mg/L, the effective filter sock life will only be two months. Of course, actual range sock life also depends on when the sock is installed in relation to dry and rainy periods.

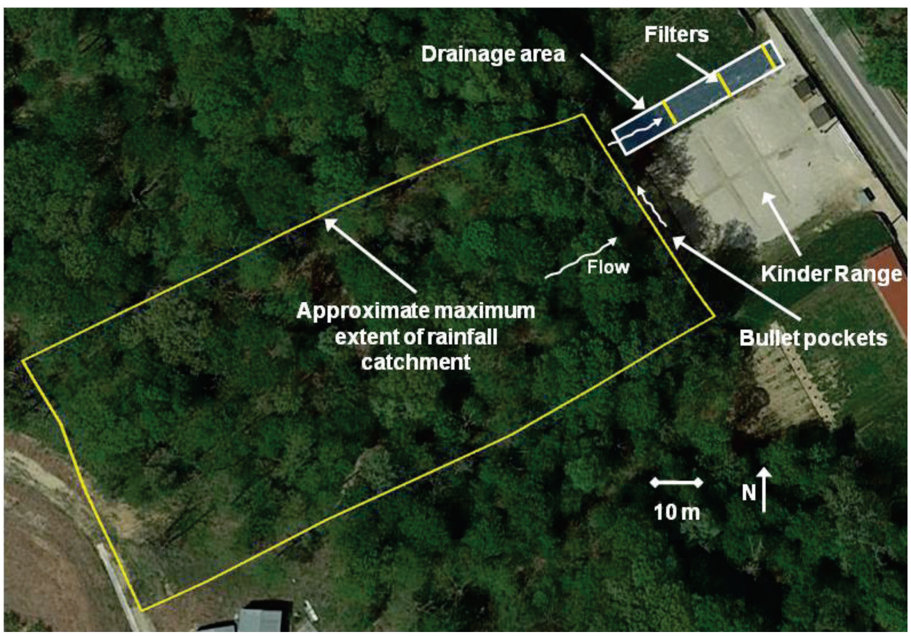
It should be anticipated that the upstream sock will need to be replaced annually. The downstream sock should last much longer, probably on the order of decades judging by the amount of TSS trapped in it relative to the upstream sock. The model for effective life does not compute estimated life for downstream socks.

Appendix B: Case Study: Fort Leavenworth, KS

B.1 Background

The Kinder Range, which is a SAFR at Fort Leavenworth, Kansas, was selected for study of filter sock performance for removing metals in range runoff. The Kinder Range presents a unique challenge due to the relatively large rainfall catchment area up-slope (i.e., upstream) of the bullet pocket area of the range. Thus, there is a considerable amount of water that flows from the catchment, which is located on a hillside, down onto the range. A view from Google Earth of the catchment and range is shown Figure 19.

Figure 19. Kinder Range and upstream catchment.



The yellow polygon shown in Figure 19 denotes the approximate maximum extent of the rainfall catchment area that contributes to runoff above the range. The catchment is on a hillside that generally slopes towards the northeast; thus, not all of this area contributes to runoff that flows onto the range. Water drains from the hillside, through the bullet pocket area, and into a ditch that flows into a relatively low and flat plain on the north side of the range. The filter socks will be located along this drainage area.

Three filter socks are being considered for placement across the drainage area as shown in Figure 19. The primary reason for having more than one filter sock is to provide substitutes for when the most upstream filter sock clogs and should be removed. The downstream socks will provide little, if any, sediment removal benefit as long as the upstream filter sock is not clogged.

B.2 Model inputs

It is estimated that roughly one third of the hillside catches rainfall that drains directly onto the range, resulting in a catchment area that is about 2,500 m^2, or about 0.6 acres. The width of the drainage area that is available for filter sock placement is approximately 6 m; thus, the length of each of the three filter socks was set to 6 m. The spacing between each filter sock was assumed to be 12 m.

The diameter of the filter socks was assumed to be 12 inches (0.3048 m). Due to the relatively large runoff, this diameter will result in water over-topping the filter sock for the average annual maximum 24-hour storm, which has a rainfall of about 2.85 inches (USDC 1961). Thus, to avoid over-topping, the decision was made to assume that two filter socks will be stacked vertically, resulting in a filter sock height of 2 ft. (0.6096 m). Also, to increase filter sock life, each of the filter socks will have an additional filter sock placed next to them resulting in a total of four filter socks; two filter socks wide and two filter socks high. Thus, the total filter sock thickness is 2 ft. (0.6096 m). This filter sock height will require some grading of the drainage channel to keep the top of the filter socks below the firing range floor.

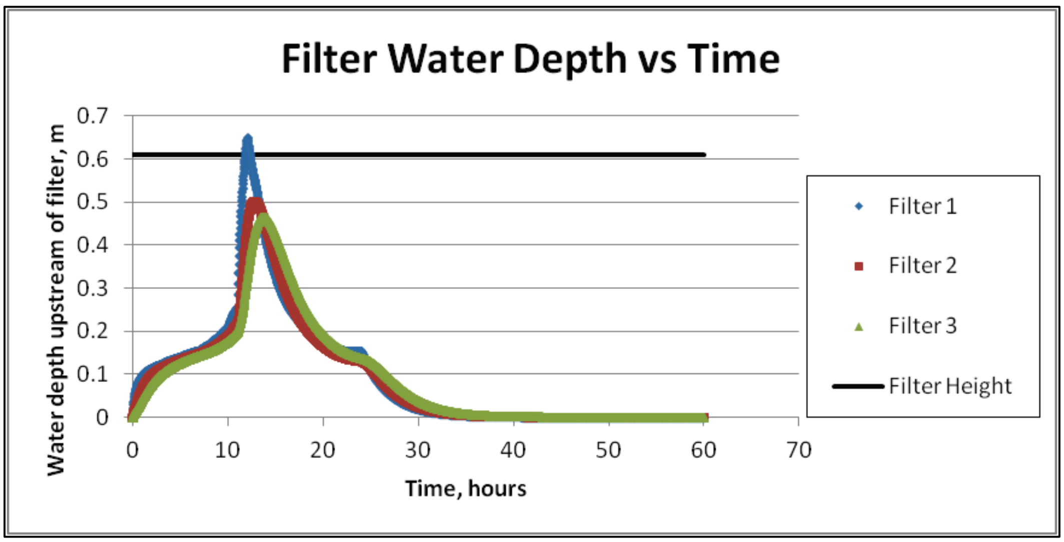
The effective sand grain size (d_{10}) of the filter sock sand was assumed to be 0.5 mm. This means that the median grain size of the filter sock sand is on the order of 1 mm, which is coarse sand. Other input parameters describing filter sock characteristics were set to the following values: sand particle shape factor (sphericity) = 0.9; sand initial porosity = 0.4; bulking factor of trapped sediment = 1.25; filter sock initial removal coefficient = 30 m^{-1}; filter sock clogging factor coefficient 1 = 6 m^{-1}; and filter sock clogging factor coefficient 2 = 1000 m^{-1}. Dortch (2013) described all input parameters in his report. The filter sock coefficients were set to values that more closely represented results of the column test described in Section 3 herein.

Other required inputs for the Kinder Range site included: rainfall depth = 2.85 inches; rainfall duration = 24-hours; storm type distribution = II; average annual rainfall = 43 inches; average number of days per year with significant rainfall (> 0.1 inches) = 90 days; *Rational Method* runoff coefficient = 0.5; ground slope = 0.046; water temperature = 13 degrees C; TSS specific gravity = 2.65; and TSS concentration in runoff = 250 mg/L based on site data.

B.3 Model results

The three filter socks versus time computed water depth of flow upstream of each sock is plotted in Figure 20. The figure shows that the maximum annual 24-hour storm results in a very slight over-topping for the first filter sock. Less frequent storms will over-top more. Storms of the same frequency, but shorter duration, exhibit peak depths that are about the same or slightly less than that shown in Figure 20; peak times are shifted left, or earlier, and the areas under the depth curves are less.

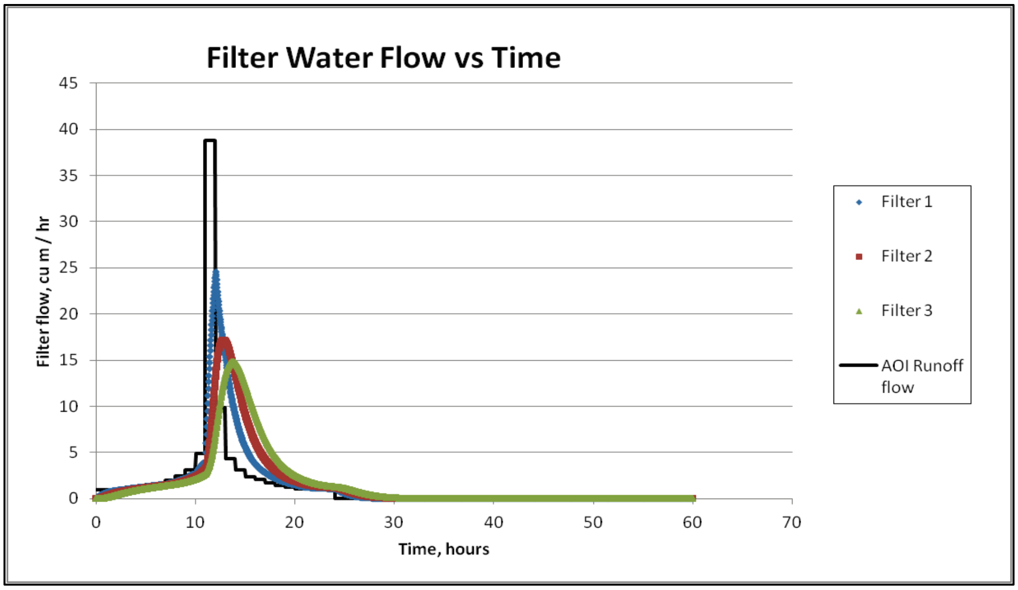
Figure 20. Computed water depth versus time immediately upstream of each sock for Kinder Range.



The computed water flow rate versus time for the catchment AOI and water flow through each filter sock are plotted in Figure 21. This figure shows how the filter socks greatly attenuate the flow rate resulting in a much lower peak flow rate, but a longer duration of flow, than the AOI runoff without the filter socks.

At the end of the 60-hour simulation, the range sock storm performance model also showed that the pore-water concentration of TSS trapped within the most upstream filter sock peaked at about 120,000 mg/L. Likewise, at the end of the simulation, the total trapped TSS mass in the most upstream filter sock was about 23 kg. The filter sock effluent TSS concentration was practically zero for all filter socks throughout the simulation; thus, for practical purposes, nearly all of the TSS in runoff was trapped. Most of the particulate metal concentration in runoff is expected to be trapped as well. Due to partial clogging, the hydraulic conductivity of the most upstream filter sock decreased from about 7 to 4 m/hr during the storm.

Figure 21. Computed water flow rate versus time for AOI and each sock for Kinder Range.



The pore-water concentration and mass of TSS trapped within the middle and last filter sock were essentially zero during the storm. For this application, it was assumed that there is no contribution of TSS in runoff downstream of the most upstream filter sock.

The model for effective filter sock life predicted that the most upstream filter sock will become ineffective for removing TSS after approximately six months. It should be recognized that this estimate of life is an approximation based on average annual rainfall and TSS concentration in runoff. An unusually wet year with multiple large storms occurring within a season could reduce the effective life. Additionally, if the TSS concentration of the runoff is greater or less, the effective life is reduced or increased, respectively. Of course, actual filter sock life depends on when the filter sock is installed in relation to dry and rainy periods.

It should be anticipated that the upstream filter sock should be removed after clogging. The middle filter sock will then remove most of the sediment, and it will clog within about six months after the most upstream filter sock clogs.

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14. ABSTRACT
Small arms firing ranges located on Department of Defense facilities are, in many cases, constructed next to wetland areas. Access to wetland areas is typically limited due to a lack of roads. Standard environmental remedial options and monitoring techniques are expensive to implement due to the nature of the terrain and seasonal changes in water flow. Metals are highly associated with the soil particles making up the total suspended solids in the runoff water. Reactive materials were assembled into a barrier similar to erosion control socks using a non-woven geotextile filled with well-graded sand, amended with five percent (weight: weight, w:w) iron/manganese-oxides (TRAPPS™) and/or five percent (w:w) treated apatite. The socks were tested under mesoscale lysimeter conditions and removal of metals from solution was confirmed. The reactive socks adsorbed greater than 95 percent of metals in the solution. Once the reactive material was exhausted, it was tested and found to pass the TCLP test for placement in a non-hazardous landfill. Sock placement was determined using predictive models for surface runoff.

15. SUBJECT TERMS
heavy metals, munitions metals, lead, antimony, geotextile, passive reactive treatment, fishbone apatite, surface runoff water, TRAPPS, TCLP, mesoscale lysimeter, partition coefficient,

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